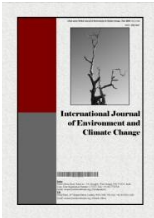

International Journal of Environment and Climate Change

11(11): 72-91, 2021; Article no.IJECC.76698
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Brown and Yellow Rust of Wheat in India – Significance of Climate on It's Races and Resistance

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2021/v11i1130517
Editor(s):
(1) Dr. Fang Xiang, University of International and Business Economics, China.
Reviewers:
(1) Ajay Vikram singh, German Federal Institute for Risk Assessment, Germany.
(2) Ana Cruz Morillo Coronado, Universidad Pedagógica y Tecnológica de Colombia, Colombia.
Complete Peer review History: https://www.sdiarticle4.com/review-history/76698

Review Article

Received 25 August 2021
Accepted 03 November 2021
Published 09 November 2021

ABSTRACT

Wheat is one of the most important staple food crops having global economic significance. Grown globally around 215 million hectares area with production of more than 600 million tons. Wheat is constrained in its production due to several biotic factors, among them yellow rust of wheat, *Puccinia striiformis* Westend. f.sp. *tritici* Eriks and Henn. (*Pst*) and brown rust of wheat, *Puccinia recondita* f.sp. *tritici* (Eriks. and E. Henn.) D.M. Henderson (*Ptr*) continues to be a serious threat and dominant factor limiting its yield potential globally. The estimated yield losses range from 10-70%, while in a severe epidemic the grain damage can be as great as 100%. Pathogens are considered to be favoured by the cooler areas but current races are more adaptable to high temperatures causing significant yield reduction in wheat. In India, prevalent pathotypes for yellow rust include 46S119, 110S119, and 238S119. Yr*5,* Yr*10,* Yr*15,* Yr*Sp, and* Yr*Sk* genes are resistant to *Pst* pathotypes in Indian conditions, while in the case of leaf rust of wheat, prevalent pathotypes are 77-5, 77-9, and 104-2. Lr*9*, *Lr19*, *Lr*24, *Lr*25, *Lr*29, *Lr*32, *Lr*39, *Lr*45, and *Lr*47 are the genes having resistance to *Ptr* pathotypes in Indian conditions. This publication provides a comprehensive overview of the stripe and leaf rusts of wheat in India and their virulent races, types of host resistance and provides a tool for effective management of wheat rust disease.

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Keywords: Wheat; Climate; leaf rust; stripe rust; race-specific; race non-specific; R-genes; pathotypes.

1. INTRODUCTION

Wheat (*Triticum* spp.) is one of the most significant crops of global economic importance. It is a basic staple food that provides everyday nourishment to millions of people across the world for millennia. Globally, wheat is the largest cultured crop with an estimated area of 220.19 mha having production of 763.2 mt and productivity of 3.25 t ha-1 (USDA, 2020). Wheat supplies almost 55per cent of carbohydrates and 20per cent of food calories for the world's growing population. In 2018-19, India recorded a historic production of 107.9.4 mt from an area of 29.55 mha and productivity as high as 3.44 t ha-1 compared to the global average of 3.25 t ha-1 (IIWBR, 2020-21). In light of the increasing food requirement due to the burgeoning population, India alone will need >140 mt of wheat by 2050 to feed an estimated population of 1.73 billion [1]. Of many biotic stresses affecting wheat and limiting yield potential, the three rust pathogens, viz. stripe or yellow rust (*Puccinia striiformis* f.sp. *tritici*), leaf or brown rust (*P. triticina*) and stem or black rust (*P. graminis* f.sp. *tritici*) are the utmost importance and potentially damaging diseases causing huge economic losses in wheat worldwide [2]. Among the three rusts of wheat, a significantly high yield reduction is brought by the stripe rust [3]. The losses in yield due to yellow rust have been estimated from 10-70 percent, while in the severe epidemic, the grain damage can be as great as 100 percent [4]. A global yield loss of about 5.5 mt year-1 was estimated due to stripe rust of wheat [5]. In the recent past, localized stripe rust epidemics with significant crop losses were reported from different major wheat-growing areas of the world, in addition to African and Central Asian regions [6].

In the past few years, increased incidences of stripe rust have been reported with greater reoccurrence, which was mainly due to the higher and faster growth rates in the population of rust pathogens, long-distance spore spreading, and development of novel pathotypes [7], [8], [9], [10]. Through the emergence of the newer and more virulent race of rust pathogens, the prevalent pathotypes are being substituted, which resulted in extensive and widespread epidemics in the current years [11]. Stripe rust remains a major biotic constraint for wheat production in Asia, menacing 43 mha of the wheat area [12]. In India, stripe rust has gained importance in the recent past especially in cooler parts, and is a threat in 10 mha area under Northern parts [1]. In the past decade, the occurrence of stripe rust in severe form was due to the evolution of new and virulent pathotypes, which were able to overcome widely used resistance in wheat [13]. During 1995-2004, the emergence of virulence (46S119) for Yr9, and virulence (78S84) for Yr9 and Yr27 led to the elimination of a mega wheat var. PBW 343, stances a threat to wheat production in India [13]. Stripe rust in severe form has been reported from plains of Jammu & Kashmir, foothills of Punjab, Himachal Pradesh, and Tarai of Uttarakhand [14]. In 2014-15, yellow rust was noticed on some popular wheat cultivars grown under plains of J&K, foothills of HP, Haryana, Punjab, Tarai of UK, and western UP, but the incidence was quite low [15].

Recently, five new *P. striiformis tritici* pathotypes, 46S117, 110S119, 238S119, 110S247, and 110S84 have been identified in India, which showed virulence on Yr11, Yr12, and Yr24 genes [16]. Race 110S119 is considered the most dominant, aggressive, and rapid population builds up ability [16]. The leaf (brown) rust is also considered the most prevalent and widely distributed of the three rusts and has major economic importance worldwide causing significant losses to the wheat crop [17]. In case of severe leaf rust infection on vulnerable wheat cultivars/genotypes, the overall yield losses may be up to 30-70per cent [18]. In India, leaf rust is most commonly occurring in all wheat growing areas and its capability to spread in Indian conditions is duly documented [1]. The present Puccinia triticina pathotypes, 77-9 (121R60-1), 77-5 (121R63-1), and 104-2 (21R55) are the most prevalent and virulence on the present-day Indian wheat cultivars [1].

Although various strategies are available to combat rust pathogens, growing host-plant resistance is considered the only effective, dominant, economical, and environmentally affable method to curb wheat rusts, besides eliminating the use of fungicides [19]. Rust resistance in wheat is generally classified into two categories: seedling resistance (also called all-stage/race-specific/qualitative resistance) and adult-plant resistance such as non-race-specific/durable/quantitative resistance [20]. In India, it has been observed that the commercially grown rust-resistant wheat varieties lose their effectiveness just after 3-5 years of their release

[21]. In the recent past, most of the cultivars deployed with a major gene for rust resistance have frequently become ineffective, because seedling resistance is mainly governed by single R-genes-based resistance. Likewise, most important and widely used wheat cultivars with stripe rust resistance gene *Yr9* in the year 1996, gene Yr27 in the year 2001, and also the leaf rust resistance conferred with gene Lr9 in the year 1999, Lr19 in the year 2004, and Lr28 in the year 2008 [13], [22], [23], [24], [25], [26]. About 70 yellow rust resistance genes have been designated so far, and out of these, only nine genes Yr18, Yr29, Yr30, Yr36, Yr39, Yr46, Yr48, Yr49, and Yr52 are associated with non-race specific/adult plant resistance [27]. Nearly 100 genes including alleles conferring leaf rust resistance genes have been known and defined [28]. The majority of the designated Lr-genes are conferring race-specific resistance (seedling stage) and stay operative across the adult plant stage (race-specific APR). Among the race-specific genes, some genes, Lr12, Lr13, Lr21, Lr22, Lr35, Lr37, Lr48, Lr49, Lr74, Lr75, and Lr77 are race-specific APR genes. Only four Lr genes, Lr34, Lr46, Lr67, and Lr68 are reported to confer non-race-specific/adult plant resistance.

1.1 About the Rust Fungi

Early records testify that Pliny, a prodigious Roman compiler of miscellaneous data on natural history in the 1st century A.D. described rust of wheat as “the greatest pest of the crops” [32], [33]. Reports of *Puccinia graminis* on wheat lemma fragments showed the archaeological evidence of rust dated 1400-12000 B.C. [34]. The Roman wheat farmers plagued by rust at that time created a god ‘Robigus’ (the god of rust) to appease and satisfy the Roman god ‘Robigus’, and a religious festival known as ‘Robigalia’ was celebrated in the spring, on 25th April of each year from about 700 B.C. until the decline of the Roman Empire.

The rust pathogens of wheat have always been the most important, widely distributed, and destructive as compared to the other crop pathogens/diseases [35], [36]. Their ability to spread aerially over greater distances under favourable environmental conditions, rapid production of infectious uredospores and the fitness to evolve novel pathotypes, and resultant epidemics causes huge and substantial losses in grain yield and yield components [1], [37].

2. TAXONOMY OF RUST FUNGUS

The rust fungi are among the most species and intricate group of plant pathogens, characterized by colored pustules resulting from uredial development of fungi belongs to the order Uredinales of family Pucciniaceae in the phylum Basidiomycota, comprises 17 genera and approximately 4121 species, of which the majority are in the Genus *Puccinia* [38]. The characteristic feature of the Family Pucciniaceae is the presence of stalked teliospores. Puccinia (after *T. Puccini*, Italian anatomist) is the largest genus with about 3000-4000 species, parasitizing angiosperms plants throughout the world [39].

In India, all three rusts occur on wheat subject to meteorological situations preponderating within a particular region/zone. Stripe or yellow rust (*Puccinia striiformis* Westend. f.sp. *tritici* Erikss.) prefers lower temperature (20°C) and dominates in cooler parts. Leaf or brown rust (*Puccinia recondita* Rob. ex. Desm. f.sp. *tritici* Eriks. & Henn.) prevails more when temperature rises (15-25°C). Stem or black rust (*Puccinia graminis* Pers. f.sp. *tritici* Eriks. & Henn.) at a higher temperature (>25°C).

3. EPIDEMIOLOGY OF WHEAT RUSTS IN INDIA

In the India the survival and perpetuation of the wheat rust pathogens are thought to occur on self-sown wheat plants and summer crops in the form of uredospores in the foot hills or southern hills. Alternate hosts of leaf rust, exclusively Thalictrum species, are common in the hills nonetheless aecial structures have not been found on these. Similarly, Berberis species occurring in hills were not found to harbour any *P. striiformis* aecial cups. It is presumed that the rust fungi have shed their alternate hosts and are known to be evolutionary further advanced than those which have functional alternate hosts [1].

4. YELLOW RUST

4.1 History and Geographical Distribution

The stripe (or yellow) rust disease was first described by Gadd and Bjerkander in 1777, but Schmidt in 1827 first described taxonomically under the name of *Uredo glumarum* infecting barley glumes [40]. Westendorp in 1854 used *Puccinia striaeformis* for stripe rust collected from rye [41]. Later on, Eriksson J. and Henning E. showed that stripe rust resulted from a separate pathogen, which they named *Puccinia glumarum*. This name of stripe rust pathogen was in the trend until reviving the name as *Puccinia striiformis* Westend. Since, the formae speciales is added after the scientific name, *Puccinia striiformis* Westend. f.sp. *tritici* Eriks. & Henn. is being used in present-day literature [42], [43]. Stripe rust is a significant disease that occurs on wheat grown in cooler environments and at higher elevations. Although, stripe rust is constricted in its distribution compared to leaf and stem rust of wheat. Yellow rust is found along with British and northwest Europe, the northwest pacific coastal area and intermountain regions of North America, a rocky mountain range in the north, cooler areas of Canada, and cooler plain area southern regions of Argentina [44]. Also, it is rampant in South America's temperate zone, central and north-western China, East Africa, Mediterranean regions, and north-western India. Besides temperate and cooler areas, stripe rust prevails in all continents except Antarctica [4].

Stripe rust is mostly considered to be a low-temperature loving disease and restricted in areas with temperate and cooler environmental conditions. But, the recent devastating epidemics in warmer areas where stripe rust was earlier uncommon or absent indicated that *Pst* populations had adapted to a higher temperature, and supporting evidence has been published by [45], [46]. In India, stripe rust is a major problem in the North-Western Plains Zone and Northern Hills Zone comprising states of Punjab, Haryana, Foothills of Himachal Pradesh, and Jammu & Kashmir, *Tarai* areas of Uttarakhand, western Uttar Pradesh, and Rajasthan. Yellow rust is mostly confined to the cooler areas of the country characterized by the prevalence of low temperature and high humidity during the crop season [1]. Stripe rust is also considered the main factor for falling wheat production in the eastern hills of Nepal [47].

4.2 Economic Importance

Yellow rust is continuing to be a serious threat and dominant factor limiting yield potential in wheat worldwide [48]. It appears in the form of the yellow stripe on leaves, causes substantial losses in yield through damaging its photosynthetic system, kills foliar parts, makes the growth of plant stunted, most importantly reduced grain weight, and affects its quality [29]. Grain losses caused by this devastating pathogen have been reported from 10-70%. In severe stripe rust epidemics, the grain damage scales up to 100% [4]. A global grain yield loss of about 5.5 mt per year have been estimated as a result of stripe rust infection in wheat crop [5]. Over the last years, localized outbreaks of stripe rust epidemics with significant crop losses were documented from different wheat-growing areas of the world, along with East and North Africa and Central and West Asia [49]. In current years, increased stripe rust incidences with high frequency have been reported because of the fast rate of evolution and rapid emergence of new rust races long-distance dispersal [50],[51], [52]. As a result of the rapid development of more virulent pathotypes, the earliest races are being superseded by new variants which have directed to a frequent and serious outbreak of stripe rust in the last few years [11].

In Asia, stripe rust remains a major constraint for wheat production, threatening 43 million ha of wheat area. In China, significant crop damage due to stripe rust have been reported from different wheat-growing regions of northwest, southwest China in the year 1950, 1964, 1990, and 2002 [53]. In 2002, a Chinese *Pst* pathotype CYR32 has triggered the most recent widespread outbreak, which has virulence to nearly all Chinese wheat varieties and avirulence on gene *Yr*5, *Yr*10, *Yr*15, *Yr*24, and *Yr*26 [54], [102], [104]. Yellow rust was reported to cause routine crop losses of between 0.1 and 5 percent with infrequent occurrences resulting in much higher losses. Stripe rust is one of the serious disease in the eastern hills of Nepal and a yield reduction of 40-78% have been reported under natural epiphytotic conditions at low altitude [47]. Safavi SA and co-workers also reported average losses of 4.4, 7.6, and 41percent in thousand kernel weight of race-specific, non-race-specific resistant, and susceptible cultivar, respectively [55]. Average grain yield losses of 65.6, 7.3, and 15.9 percent were also reported in susceptible, race-specific, and slow rusting genotypes, respectively. Vergara-Diaz O and co-workers also estimated grain yield losses in yellow-rusted durum wheat cultivars using digital and conventional parameters in field conditions [56]. They found that the presence of stripe rust disease was positively correlated with the reductions in the number of grains per spike, grains per square meter, kernel weight, and harvest index. Grain yield losses in the presence of yellow rust were also found greater in the later heading wheat varieties.

In India, yellow rust has gained importance particularly in NWPZ and NHZ due to favourable weather conditions (low temperature and high humidity) and poses a potential threat to the wheat crop of these areas [57]. Wheat rust epidemics in India have been documented by Nagarajan S and Joshi LM [37]. In 2001, the breakdown of *the Yr*27 gene with the appearance of a new variant of *Pst* race 78S84 created distress of stripe rust epidemic due to wide cultivation of wheat cv. PBW 343 [13]. In 2010-11, stripe rust occurred in a severe form in plains of Jammu and Kashmir, foothills of Punjab and Himachal Pradesh, and Tarai region of Uttarakhand, but timely action on monitoring its spread through fungicide protected the crop from major damage [37]. During 2014-15, stripe rust again appeared on some popular wheat cultivars planted in plains of Jammu & Kashmir, foothills of HP, Haryana, Punjab, *Tarai* of UK, and western UP [15].

Fig. 1. Yellow rust characteristic symptoms: Streak contains amount of elliptical, lemon shaped yellowish pustules lined lengthwise with the veins

4.3 Symptomatology

This disease is distinguished by yellowish pustules resulting from uredial development, arranged in the form of narrow, yellow, linear streaks primarily on the leaf blade. In case of extreme infection, pustules can occur on leaf sheath, stalk, glumes, awns, and ear heads which rarely infest the developing grains. Streak contains an amount of elliptical, lemon-shaped yellowish pustules lined lengthwise with the veins, while under severe infection, streak patterns become indistinguishable as the uredo-pustules arranged into clusters. Pathogen on infecting leaf lamina remains partially systemic and the stripes keep on enlarging. Uredospores never break through the epidermis as immediately as in the case of other rust, but eventually act like, exposing a yellow spore mass to wind dispersion [1]. Later on, these stripes turn black when teliospores are formed. Telia is dull black, appears mostly beneath the leaf exterior, besides on other portions of the plant. Like uredia, telia are also organized in long stripes and wrapped by the host epidermis as a smooth blackish incrustation [58].

4.4 Cycle of Infection of the Pathogen

4.4.1 Yellow rust

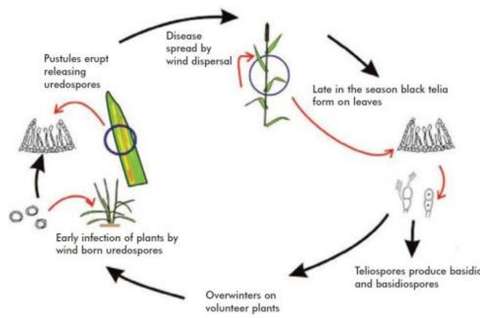

Fig. 2. Shows the Infection cycle of yellow rust pathogen.[55], [59], [132]

4.5 Physiological Races

Hungerford and Owens were the first to report 'specialized varieties' occurred in *P. striiformis* based on specificity on genera of wheat and grasses [133]. However, was the first to establish the existence of races in *P. striiformis* f.sp. *tritici* based on specificity on wheat cultivars. The designation of isolates into distinct races using differential sets was originally proposed for *P. striiformis tritici* in Germany in the 1930s. In the US, about 109 races (PST1-PST109) of *Pst* were identified, among which 59 were identified before, and 50 since the year 2000 [4]. In China, a total of 67 races have been identified based on their virulence and avirulence patterns on the 17 differential lines [60]. In India, Nagarajan S and co-workers established the system for pathotype analysis and designation of *P. striiformis* f.sp. *tritici* races [37].

Pathotypes identified so far in India	**13(67S8), 14(66S0), 14A(66S64), 19(70S0-2), 20(70S0), 20A(70S64), 24(0S0-1), 31(67S64), 38(66S0-1), 38A(66S64-1), 57(0S0), A(70S4), G(4S0), G-1(4S0-3), I(38S102), K(47S102), L(70S69), M(1S0), N(46S102), 46S119(46E159), 78S84, P(46S103), Q(5S0), T(47S103), U(102S100), CI (14S64), CII(15S64), CIII(78S64), 110S119(110E159), 46S117, 110S247, 110S84 and 238S119**	**References [16] [1]**
Recently identified Pathotypes in India	46S117, 110S119, 238S119, 110S247 and 110S84 **Virulent on:** *Yr*11, *Yr*12 &*Yr*24	[16]
Pathotype 46S119 followed by 78S84	**Virulent on:** *Yr*9 gene in 1996 broken the resistance of PBW 343	[16] [1]
Pathotypes 46S119	**Virulent on:** *Yr*27 gene	[16]

Race 110S119 is the most dominant, aggressive, and also has fast population build-up ability [16]. I(38S102) is the major race in Southern Hills Zone but is not yet reported from other zones of the country [13].

5. BROWN RUST

5.1 History and Geographical Distribution

The leaf rust on wheat was originally identified as distinct species from other wheat rusts and defined as Uredo rubigo-vera by De Candolle [61]. Later it was placed in the species complex, *Puccinia rubigo-vera* by Winter [62]. In 1894, Eriksson and Henning described leaf rust as *P. dispersa* which included wheat and rye leaf rust. In 1899, Eriksson was the first to define leaf rust fungus as a single species, specific to wheat and named *P. triticina*. Cummins, G.B. and Caldwell, R.M. merged wheat leaf rust in the species complex of *P. recondita* and further subdivided it into formae speciales based on host range, and wheat leaf rust was placed into *P. recondita* f.sp. *tritici* [63], [64]. Based on sexual incompatibility, the leaf rust pathogen of wheat is now considered a species different from leaf rust occurring on rye and other wheat relatives. This separation of wheat leaf rust from *P. recondita* is reinforced by phylogenetic ribosomal DNA sequence analyses, spore morphology, and infection structure morphology [65], [66], [67]. Since then, the leaf rust pathogen of wheat is renamed and designated as *Puccinia triticina* Eriks.

Wheat leaf rust is the most common and prevalent in almost all wheat-growing regions across the world compared to stripe or stem rust of wheat [68]. Leaf rust is a major production constraint in North Africa, Asia (central, south, and southeast), Europe, North, and south Americas, Australia, and New Zealand [69]. Based on airborne dispersal of uredospores by the wind in each cropping year, the world's wheat-growing areas were divided into 9 epidemiological regions, Mexico, Canada, and the USA, South Asia, West Asia, Eastern Europe, and Egypt; Southern Africa; Northern Africa and Western Europe; the Far East; Southeast Asia; South America; and Australia-New Zealand. Based on the diversity in the pathogen population, the above regions were further divided [2].

5.2 Economic Importance

The importance of leaf rust was noticed, when it rendered the wheat variety 'Thatcher' in 1938 and devastated millions of hectares of the wheat crop across North America. Since then, leaf rust was considered the most damaging disease in wheat-growing areas of the USA, the former USSR, and China (Chester, 1946). In the US, economic losses inflicted due to leaf rust were valued at >3 Mt between 2000 and 2004, worth >$350 million [70]. In Mexico, durum wheat is the most affected crop with leaf rust, and the emergence of a non-native race BBG/BN caused huge yield losses worth $32 million from 2000 to 2003, and again $172 million from 2008 to 2009. In South America (Argentina, Brazil, Chile, Paraguay, and Uruguay), leaf rust is responsible for about $172 million of losses in the year from 1996 to 2003 [71]. Although, leaf rust is not yet reported as a problematic disease in Western Europe, while in Eastern Europe it is considered as an utmost destructive disease [72].

In China, brown rust appears on approximately 15 Mha areas yearly and causes an average yield loss of about 3 Mt annually [70]. In Australia, it appears throughout all wheat-growing areas and causes an estimated average annual loss of $913 million [73]. Also, an estimated future nationwide loss of $197 million and actual losses of $12 million have been reported due to this disease [74]. In Uruguay, the wheat cultivar La Paz resulted in yield losses of >50 percent due to the severe leaf rust epidemic [70]. In Pakistan during 1973, leaf rust intensities ranged from 40-50 percent with 100 percent infection occurring on susceptible wheat varieties and caused a 10 percent production loss estimated at $86 million [75].

In India, leaf rust is widely spread and frequently occurs in varying intensities among the three wheat rusts across the country. Epidemics of leaf rust in India have been documented every so often during the years 1786, 1805, 1827, 1832, 1894, 1897, 1905, 1947, 1948, 1956, 1972, and 1973 [76]. Severe outbreaks of leaf rust occur in different areas under the north-western zone of the country in the year from 1971-1972 and 1972-1973, an estimated loss of 0.8 to 1.5 Mt, respectively for variety Kalyansona, K68, and Sonalika have been reported [76]. In 1978, the leaf rust epidemic occurred in northwestern India on popular var. WL 711 [77], but WL 711 continued to be grown long after this. Leaf rust epidemic in 1980 on cultivar Sonalika in different parts of Bihar and Uttar Pradesh, resulted in an estimated loss of 1 Mt of wheat [78]. A total yield loss of 30-40 percent has been reported because of a reduction in thousand-grain weight due to serious leaf rust infection in the wheat crop [79].

5.3 Symptomatology

The leaf rust disease mostly develops as small, spherical to ellipsoidal, yellowish-brown to orangish-brown uredial pustules on the upper surface of the leaf blade in a random scattered distribution. While in serious cases, it may group into patches. Sometimes it could also appear on leaf sheath, peduncles, internodes, and ear heads. Pustules are formed more often on the abaxial surface of the leaf than on the adaxial surface. Although, in the case of highly susceptible cultivars it may be found on both leaf surfaces [2]. In severe leaf rust infection, it reduces the grain number per spike which resulted in the loss of kernel weights [80],[81], [82]. Teliospores are small, oval, or rectangular and dull black color, remain in leaf tissues covered by the epidermis and arranged in groups separated by paraphyses [83].

Fig. 3. Small, spherical to ellipsoidal, yellowish-brown to orangish-brown uredial pustules on upper surface of the leaf blade in a random scattered distribution

5.4 Cycle of infection of the pathogen.

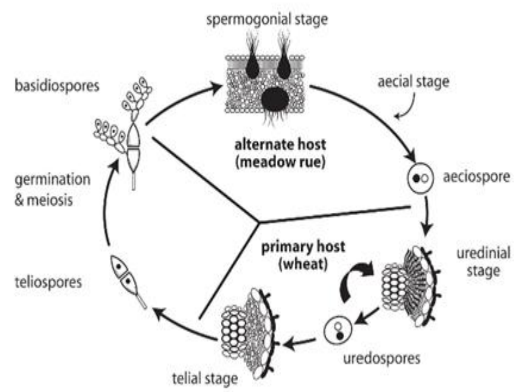

Fig. 4. Shows the Infection cycle of brown rust pathogen [84],[85], [83]

5.5 Physiological Races

The physiological specialization in *P. recondita* was first demonstrated by Jackson and Mains. Twelve races were identified based on infection types produced on differential wheat host cultivars in the USA [86].

Czechoslovakia races identified are	**UN 2-62 and UN 2-15, UN 3-61SaBa, UN 3-61, UN 3-58, UN 3-61/58, UN1 0-11, UN 10-14, UN 10-38 UN 13-77, UN 17-167 predominate** **UN 3-61SaBa race found in 43 samples analysed**	**References [82]**
US	70 races from 20 differential lines	[87]
France	30-50 races	

In India, K.C Mehta was the first to initiate investigations on physiological races of rusts at Flowerdale (Shimla) in 1931s.

Predominant pathotypes identified so far from India	**10 (13R19), 11 (0R8), 12 (5R5), 12-1 (5R37), 12-2 (1R5), 12-3 (49R37), 12-4 (69R13), 12-5 (29R45), 12-6 (5R45), 12-7 (93R45), 12-8 (49R45), 12-9(93R37), 12A(5R13), 16 (0R0-7), 16-1(5R9-7), 17 (61R24), 20 (5R27), 63 (0R8-1), 77 (45R31), 77-1 (109R63), 77-2 (109R31-1), 77-3 (125R55), 77-4 (125R23-1), 77-5 (121R63-1), 77-6 (121R55-1), 77-7 (121R127), 77-8 (253R31), 77-9 (121R60-1), 77-10 (377R60-1), 77-11 (125R28), 77A (109R31), 77A-1 (109R23), 104 (17R23), 104-1 (21R31-1), 104-2 (21R55), 104-3 (21R63), 104-4 (21R57), 104A (21R31), 104B (29R23), 106 (0R9), 107 (45R3), 107-1 (45R35), 108 (13R27), 108- (57R27), 162 (93R7), 162-1 (93R47), 162-2 (93R39), 162-3 (29R7) and 162A (93R15).**	**References [90]**
US	70 races from 20 differential lines	[87]
France	30-50 races	

Among these, three races **77-9 (121R60-1), 77-5 (121R63-1),** and **104-2 (21R55)** are considered the most prevalent and virulence on the current wheat cultivars in India (Bhardwaj et al., 2019). In Nepal, the races are more or less similar to those identified in India. During 2005-2008, frequency of race 21R55(104-2) followed by 121R63-1(77-5) were common [88], [89], [90], [121], [131].

6. MANAGEMENT ASPECTS

6.1 Cultural Practice

Using a series of cultural practices significantly enhances the existing sources of resistance. As a result, crop management in terms of a combination of crop choice, the timing of seeding, and removing volunteer cereals may provide effective control of leaf rust [134].

6.2 Chemical Control

Among the numerous approaches available to combat this disease, the use of either fungicides or host resistance has been the most important and widely used component of rust management strategies in wheat. Application of fungicides provides an effective and applied means of controlling rust outbreaks or epidemics, particularly when resistant cultivars are unavailable or when existing cultivars' resistance is rendered because of the emergence of new and more virulent rust pathotypes [91]. Also, fungicides get first preference when susceptible varieties are grown, as it provides rapid and effective control of the disease. Triadimefon (Bayleton) has been extensively used for control of stripe rust in North America in 1981s, which prevented multimillion-dollar losses [29]. Several different fungicide molecules Tilt (Propiconazole), Bayleton (Triadimefon), Folicur (Tebuconazole), Evito (Fluoxastrobin), Quadris (Azoxystrobin), Prosaro (Prothioconazole + Tebuconazole), Stratego (Propiconazole + Trifloxystrobin) and Quilt (Azoxystrobin + Propiconazole), etc. have been recently registered and found highly effective in controlling all the three rusts worldwide.

Singh co-workers recorded the lowest mean stripe rust severity (1.22 percent) with the max mean disease control (98.67 percent) with the application of a strobilurin fungicide Azoxystrobin 25SC (Amistar @ 0.1 percent). Although numerous high-efficiency fungicides are available for controlling stripe rust, its widespread and injudicious use enhances the substantial cost to wheat production, including an adverse effect on health and environment, development of fungicide resistance in pathogen and uplifts the discriminating consequence on pathogen populations which results towards the development of more virulent races [19], [92].

6.3 Biological Control

The bacterial strain, Pseudomonas putida has the capability to produce several types of antibiotics, siderophores, and a slight quantity of hydrogen cyanide (HCN), which suppresses the Puccinia triticina growth in vitro and vivo [134].

6.4 Pathogen Monitoring

Pathogen monitoring allows the early detection of new races and confirms the prevalence of major existing races and the information obtained from it informs policies, research, and development investments, as well as crop protection and breeding approaches [134].

Growing cultivars with an adequate level of genetic resistance have been considered the most preferred way of rust control, as it is also the most efficient, economic, and environmentally safe method to eliminate the use of fungicides and curtail losses due to the rusts [4], [136].

7. PYRAMIDING OF RUST RESISTANCE GENES FOR THE RUST PATHOGENS

Although different rust resistance genes are available in various backgrounds, in many cases useful resistance is associated with genetic drag. Because rust resistance genes such as Lr9, Lr19, Lr26, and Yr9 have been rendered ineffective, other genes are needed in desirable backgrounds to combat wheat rusts [135].

Genetic stocks with pyramided rust resistance in good agronomic background [1]

S. No.	Title (INGR Number)	Year of Notification	Resistance to Wheat Rusts	Remark/Resistance Gene
1.	FLW1 (03013)	2003	Resistant to leaf, and stem rusts	Lr24 + Sr24
2.	FLW2 (03014)	2003	Resistant to leaf, stripe, and stem rusts	Lr24 + Lr26 + Sr24 + Sr31 + Yr9 + Yr27
3.	FLW8 (04012)	2004	Resistant to leaf, and stem rusts	Lr19+ Sr25
4.	HW2002(04014)	2004	Resistant to leaf, and stem rusts	Lr24/Sr24
5.	FLW13 (05005)	2005	Resistant to leaf, stripe and stem rusts	Lr34 + Sr2 + Yr15 + Yr18
14.	FLW15 (05006)	2005	Resistant to leaf, stripe and stem rusts	Lr26 + Lr32 + Sr31 + Yr9 + YrPBW343
16.	FKW1 (06004)	2006	Resistant to leaf, stripe, and stem rusts	Lr26 + Sr31 + Yr9 + YrChina-84
19.	FLW24 (07005)	2007	Resistant to leaf, stripe, and stem rusts	Lr19 + Lr26 + Sr25 + Sr31 + Yr9 + Yr27
23.	FLW28 (08001)	2008	Resistant to leaf and stripe rusts	Lr19 + Lr24 + Lr26 + Sr24 + Sr25 + Sr31 + Yr9
29.	FLW21(INGR17008)	2017	Resistant to all wheat rusts	Lr26 + Lr24 + Sr24 + Sr31 + Yr9 + Yr15
30.	FLW22(INGR17009)	2017	Resistant to all wheat rusts	Lr26 + Lr28 + Sr31 + Yr9 + YrChina-84

8. RUST RESISTANCE FACTS

Through the finding of the genetic basis of resistance by Biffen in 1905, the physiological specialization in rust fungi by Stakman EC and the gene-for-gene hypothesis by Flor HH, the exploitation of race-specific/hypersensitive type of resistance has been conquered in wheat improvement programmes across the world [92], [103]. This way of dealing with rust appears to be very captivating in the viewpoint of disease-free crops and also as it is very easy to deploy into improved germplasm. But the continuous destruction of such resistance types/genes or their mixtures directed researchers in the search for alternative ways to manage resistance. The multilineal concept was publicized by Caldwell RM and Jenson NF [94], [95]. appeared out of the difficulties associated with the repeated breakdown of the major gene-based race-specific resistance. Van der Plank was the leading epidemiologist to distinctly elucidate the conceptual basis of host-plant resistance. Lately, during the 1960s and 1970s, there was a renaissance of the conception of general (non-race-specific) resistance and their utilization in crop improvement [96]. Thereafter, this approach was globally applied in developing resistance against leaf rust and stripe rust [96], [97].

Two distinct categories of genetic resistance, namely race-specific and non-race-specific resistance to rust pathogens differing in the mechanism of functioning and their epidemiological significances are classified by Vanderplank JE [20]. In addition, related non-host species are constantly being exploited to characterize new resistant sources referred to as 'non-host resistance' [98].

Race-specific resistance provides highly efficient protection to very few but not all races of a rust pathogen and generally depends on a specific recognition event between the host and the pathogen following gene-for-gene interaction but are not considered durable [99]. Race-specific resistance can be detected at the seedling stage but is also expressed at all growth stages of the plant, hence called all-stage resistance, it's because all-stage resistance is often conferred by single genes. Most of these genes can be detected in seedling evaluations using specific pathotypes, however, detection of a few others requires testing at post-seedling growth stages. Race-specific resistance is last very rapidly due to the fast evolution of new virulences by the pathogens especially, when a single *R*-gene is deployed over a large area [58]. Many race-specific rust-resistant genes have been defined genetically and catalogued by McIntosh RA [111]. Example for race-specific resistance in wheat HS 628, PBW 725, PBW 752, PBW 756.

Non-race-specific resistance is manly polygenic, durable, often quantitatively inherited, effective at the adult plant stage, and operate against all pathotypes of a pathogen [4]. The genetic nature of this type of rust resistance is usually complex and based on the additive interaction of a few or several genes having minor to intermediate effects. This type of resistance is generally defined as adult plant/slow rusting/partial resistance and is known to be more durable [2]. Slow rusting is almost as same as partial resistances. Slow rusting defines as a type of resistance in which disease develops at a slow pace, resulting in moderate to low disease levels against all races of the pathogen [96]. Partial resistance is defined as a form of incomplete resistance that represents a reduced rate of disease/epidemic development despite a highly susceptible infection type [100]. Durable resistance is remained standing effective even after its wide-scale cultivation for a long time in areas/regions conducive to disease development [101]. Several mechanisms are operative in the slow rusting of a cultivar, such as extended latent period, low sensitivity/infection frequency, smaller uredial size and reduced spore production and their quantity. All these components can influence disease progress under field conditions. Example for Non-race-specific resistance in wheat PBW 756, HD 3086, HD 3226, HI 1620, DBW 187, WH 1124, HI 1628, HS 562 RAJ 4496 MACS 6222.

8.1 Resistance to Stripe Rust

Biffen RH co-workers were the first to demonstrate the stripe rust resistance follows Mendel's laws. Most of the resistance genes were identified after the 1960s. More than 70 stripe rust resistance genes have been identified and designated as *Yr* followed by a number, letter, or symbol [103].

linked genes for rust resistance	*Sr*2/*Lr*27/*Yr*30; *Sr*15/*Lr*20; *Sr*23/*Lr*16; *Sr*24/*Lr*24/*Yr*71; *Sr*25/*Lr*19; *Sr*31/*Lr*26/*Yr*9; *Sr*38/*Lr*37/*Yr*17; *Sr*39/*Lr*35;*Lr*57/*Yr*40; *Lr*62/*Yr*42;*Lr*25/*Lr*48, *Yr*51/*Yr*60, *Lr*26/*Sr*31/*Yr*9/*Pm*8 (largely utilised gene), *Lr*24/*Sr*24, *Lr*19/*Sr*25, *Lr*37/*Sr*38/*Yr*17 (ultimate source of APR), *Lr*52/*Yr*47.	(Wheat Gene Catalogue 2013; 2013-14 Supplement; 2015-16 Supplement; 2017 Supplement; [105].
Pleiotropic APR genes (PAPR)	Locus ***Lr*34/*Yr*18/*Sr*57/*Pm*38/*Sb*1/*Bdv*1/*Ltn*1** on chromosome 7DS ***Lr*67/*Yr*46/*Sr*55/*Pm*46/*Ltn*3**on chromosome 4DL ***Lr*46/*Yr*29/*Sr*58/*Pm*39/*Ltn*2** on chromosome 1BL All these three PAPR genes are associated with leaf tip necrosis (*Ltn*) which can serve as a phenotypic marker for keeping track of them in breeding populations.	Imparting resistance to leaf rust, stripe rust, stem rust, powdery mildew, spot blotch, and barley yellow dwarf
In India, stripe trust resistance genes	*Yr*2, *Yr*9 and *Yr*18 *Yr*5, *Yr*10, *Yr*11, *Yr*12, *Yr*13, *Yr*14, *Yr*15, *Yr*16, *Yr*sp and *Yr*sk	

Stripe rust resistance (*Yr*) gene is generally divided into two general categories as race-specific/seedling/all stage resistance conferred by single dominant genes is usually provided with a high level of resistance, but popularity lost eventually once after widely cultivated in larger areas due to emergence of new virulences of the pathogen [112]. An alteration in virulence pattern and rapid development of new races may break the resistant genes and make them susceptible, mostly because of their race-specific nature [106]. In India, it has been observed that the commercially grown rust-resistant wheat varieties lose their effectiveness just after 3-5 years of their release [79]. Several wheat cultivars inbuilt with race-specific resistance genes have been reported unsuccessful in recent past years. Like, failure of the most important and broadly used resistance genes *Yr*9 in 1996 [107]. followed by *the Yr*27 gene in 2001 [13]. Breakdown of leaf rust resistance genes *Lr*9 in 1999, *Lr*19 in 2004 [25]. and *Lr*28 in 2008 [24]. Abundant energy has been wasted towards studies on genetic race-specific rust resistance, while numerous sources of non-race-specific/adult plant resistance are yet untouched and need to be identified [108].

Non-race-specific/adult plant resistance controlled by many minor genes provides durable resistance but is partial and difficult to incorporate into new cultivars. Hence, a combination of the two types of resistance genes/3-4 genes in wheat cultivars has become essential to develop as a highly efficient, durable and long-lasting resistant cultivar [26]. Among the *Yr* genes designated so far, only a few genes, *Yr*18, *Yr*29, *Yr*30, *Yr*36, *Yr*39, *Yr*46, *Yr*48, *Yr*49 and *Yr*52 are associated with non-race-specific/adult plant/durable resistance [27]. *Yr*36 is a non-race specific and HTAP resistance gene located on chromosome 6B and was derived from *Triticum turgidum* var. *dicoccoides* [109]. *Yr*39 is also a non-race specific and HTAP resistance gene identified in cultivar Alpowa with a chromosomal location at 7BL. *Yr*48 gene is identified from synthetic wheat 205 and located on chromosome 5AL, and having partial yellow rust resistance gene effective at the adult plant. *Yr*49 gene was identified in AvocetS*3/Chuanmai18AUS91433 and located on chromosomal 3DS [110]. *Yr*52 is a new gene that confers HTAP resistance to yellow rust, located on chromosome 7BL, which was identified in spring wheat germplasm PI-183527 [111]. Race non-specific resistance does not provide the host plant with complete protection, instead, it typically operates at the adult plant stage and is associated with the increased latent period, lower infection frequency and sporulation duration, smaller uredinial size and reduced spore production [29].

8.2 Resistance to Leaf (brown) Rust

More than 100 leaf rust resistance (*Lr*) genes have been described in wheat and its relative genomes [112]. Among these, 79 genes are permanently catalogued in wheat [113]. The genes *Lr*10, *Lr*14a, *Lr*18 are reported as temperature-sensitive and mostly operative at a lower temperature, whereas *Lr*16, *Lr*17, *Lr*23 are active at higher temperatures [114].

In India, Nagarajan co-workers documented rust resistance genes in wheat material, afterward, updates were published and available [90]. During this period, various research workers-initiated studies on the genetics of wheat rust resistance and diverse information observed were added. Based on available information, it can be considered that the leaf rust resistance of Indian wheat material is based on *Lr*1, *Lr*3, *Lr*9, *Lr*10, *Lr*13, *Lr*14a, *Lr*17, *Lr*18, *Lr*19, *Lr*22, *Lr*23, *Lr*24, *Lr*26, *Lr*28, *Lr*34, *Lr*46 and *Lr*49. Among these, *Lr*26, *Lr*13, *Lr*23 and *Lr*34 have been characterized in many wheat lines. Currently, *Lr*24, *Lr*25, *Lr*29, *Lr*32, *Lr*39, *Lr*45, *Lr*47 are resistant to the Indian population of *P. tritici*na. Genetic resistance to leaf rust is generally divided into three general categories as:

Race-specific resistance genes: The majority of the designated genes are characterized as havingrace-specific resistance genes, e.g., *Lr*1, *Lr*3, *Lr*9, *Lr*15, *Lr*19, *Lr*20, *Lr*23, *Lr*24, *Lr*25, *Lr*26, *Lr*28, *Lr*29, *Lr*30, *Lr*32, *Lr*36, *Lr*39, *Lr*42, *Lr*45, *Lr*47 and *Lr*51 etc.

Race-specific adult plant resistance genes: Among the race-specific genes, some genes, *Lr*12, *Lr*13, *Lr*21, *Lr*22, *Lr*35, *Lr*37, *Lr*48, *Lr*49, *Lr*74, *Lr*75 and *Lr*77 are race-specific APR genes. *Lr*12 gene was firstly derived from cultivar Exchange and located on chromosome 4B [115].

Non-race-specific/Adult plant resistance genes: At present, only four *Lr* genes, *Lr*34, *Lr*46, *Lr*67 and *Lr*68 are reported to confer race non-specific/adult plant slow rusting resistance.

Lr13 gene	Identified from the cultivar Fontana and located on chromosome 2BS	
***Lr*21**	*T. tauschii*var. *meyeri*RL5289, chromosomal location is 1D	[116]
***Lr*22a gene**	*T. tauschii*var. *strangulata*RL5271 and located at chromosome 2DS	[132], [116]
***Lr*22b gene**	Identified from common wheat cultivar Marquis It was also found in other cultivars Canthatch, Marquis and Thatcher	[117].
Lr35 gene	Was formerly identified from *T. speltoides and* located on chromosome 2B	[118].
***Lr*37/*Sr*38/*Yr*17**	Derived from *T. ventricosum*.	[119].
***Lr*48 gene**	Mapped in CSP44 on chromosome arm 2BS and it is hypersensitive APR genes which is recessive in nature	[120].
***Lr*49**	Derived from VL 404, located on chromosome arm 4BL	[120]
	Non-race-specific/Adult plant resistance genes	
***Lr*34**	Located on chromosome arm 7D and also linked to *Yr*18 and with barley yellow dwarf virus. In addition, it attributed the adult plant resistance of Chinese Spring and Sturdy to the interaction of *Lr*12and*Lr*34 *Lr*34 has been identified in wheat from Iran, China, Afghanistan, Lebanon, Russia, Argentina, Tunisia and France.	[6],[122] [123] [114] [82]
***Lr*46** ***Lr*46/*Yr*29 gene**	Rises the latent period and reduces infection rates and lowers the uredial size as like as to *Lr*34. The linkage between *Lr*46/*Yr*29 is also similar to linkage between APR genes *Lr*34/*Yr*18 Identified from cultivars Pavon-76 and was mapped at the distal end of the long arm of chromosome 1BL. It is tightly linked with stripe rust APR gene *Yr*29	[124] [6] [124]
***Lr*67/*Yr*46/*Sr*55gene** ***Lr*68 gene**	Designated in a stock RL 6077 (Thatcher*6/PI 250413) and located at chromosome arm 4DL. Identified from Parula, located on chromosome 7BL	[125] [130]

9. EVALUATION AND CHARACTERIZATION OF RUST RESISTANCE IN WHEAT

Rust resistance evaluation is a continuous process to identify new effective sources and further their utilization in the rust resistance breeding programme for the development of effective and durable rust-resistant wheat varieties to combat rust pathogens [126]. Wheat materials are screened against rust pathogens for resistance at the seedling stage under controlled conditions and adult plant stage under field conditions.

9.1 Seedling Rust Resistance Evaluation

Screening of wheat germplasm at the seedling stage is the fastest and reliable method for selecting the resistant lines against rust pathogens. A large number of pre-breeding/advanced lines/exotic and other materials of wheat are screened at the seedling stage for their resistance against different pathotypes of rust pathogens. Seedling resistance evaluations are also performed for characterization/gene postulation of rust resistance genes in wheat lines. The presence of rust resistance genes (*Yr*, *Lr and Sr* genes) can be postulated by utilizing a gene-matching procedure using multi-pathotype infection type patterns. Sharma and co-workers found *Yr*2 and *Yr*7 in a seedling test of 11 Indian wheat cultivars using 17 pathotypes and confirmed the presence of *Yr*2 in three cultivars by testing the F1 and F2 generations of crosses between these cultivars and Heines VII, a cultivar that contains *Yr*2 [127]. Draz IS and co-workers inoculated seedlings of 38 wild emmer derivatives and 53 advanced wheat lines from Nepal with 18 *Pst* pathotypes and found 28 wild emmer derivatives were resistant to all pathotypes with unidentified resistance genes, and five resistance genes (*Yr*2, *Yr*6, *Yr*7, *Yr*9, and *Yr*A) were prevailing in tested wheat cultivars and advanced Nepal lines [128]. Genes *Yr*2, *Yr*3a, *Yr*4a, *Yr*6, *Yr*7, *Yr*9, *Yr*26, *Yr*27, and *Yr*SD, singly or in combinations, were postulated in 72 lines, while known resistance genes were not recorded in the other 26 accessions. The resistance genes *Yr*9 and *Yr*26 were found in 42 and 19 accessions, respectively. *Yr*3a gene and *Yr*4a gene were noticed in two lines, and four lines may contain *the Yr*6 gene.

Three lines were postulated to possess *the Yr*SD gene, one carried *the Yr*27 gene, and one may possess *the Yr*7 gene. Thirty-three lines showed slow stripe rusting resistance [54]. Herrera-Foessel SA and co-workers observed that the latent period was significantly longer 8.5-10.3 days and uredinium size suggestively smaller 8.1-14.8 × 10-2 mm2 on slow rusting durum wheat than on the susceptible checks 8.0 days and 17.3-23.8 × 10-2 mm2, respectively [130]. Uredinium size was the most stable slow rusting factor across experimentations. Bhardwaj SC and co-workers characterize different combinations of seven leaf rust resistance genes, *viz. Lr*1, *Lr*3, *Lr*10, *Lr*13, *Lr*23, *Lr*26, and *Lr*34 gene by applying the gene-matching technique in 39 wheat lines that showed race-specific APR to one and/or other pathotypes [24]. Using controlled inoculation with ten pathotypes of *Puccinia triticina*, 14 seedling resistance genes were postulated. *Lr*1, *Lr*3, *Lr*10, and *Lr*20 were the most prevalent genes across the world while *Lr*9, *Lr*14b, *Lr*3ka, and/or *Lr*30 and *Lr*26 were rare [53]. Three different combinations of yellow rust resistance genes, *the Yr*2 gene, *Yr*9 gene, and *Yr*18 gene have been characterized from Indian wheat materials [17].

9.2 Adult Plant Rust Resistance Evaluation

Adult plant resistance is now a chief interest among wheat scientist around the world as its resistance is quantitative and durable that protect for a long period. The quantitative aspects of this type of host resistance have been described and evaluated utilizing disease severity and response at a certain growth stage, coefficient of infection, area under the disease progress curve, apparent infection rate, or through latent period [108], [49]. Safavi SA and coworkers studied the effect of stripe rust on the yield of seedling and partial resistant wheat genotypes and reported significant variances among genotypes [55]. Genotype with partial resistance showed low values of epidemiological parameters. Out of 41 monogenic lines tested, only 13 *Lr* genes (*Lr*9, *Lr*10, *Lr*11, *Lr*16, *Lr*18, *Lr*19, *Lr*26, *Lr*27, *Lr*29, *Lr*30, *Lr*34, *Lr*42, and *Lr*46) displayed seedling resistance while, 9 *Lr* genes (*Lr*19, *Lr*20, *Lr*21, *Lr*24, *Lr*29, *Lr*30, *Lr*32, *Lr*34, and *Lr*44) exhibited adult plant resistance [129]. Singh VK and co-workers also conducted a field-based appraisal of partial resistance against stripe rust and characterized different levels of resistance using different epidemiological parameters estimates [49]. Freshly, assessed 62 exotic wheat germplasm and measured the levels of adult plant slow rusting resistance under field conditions through host response and epidemiological parameters estimates *i.e.,* final rust severity, coefficient of infection, the relative area under disease progress curve, and apparent infection rate. They reported hopeful slow rusting resistance on the germplasm *viz.,* CIMCOG 1, 2, 3, 5, 6, 7, 12, 14, 15, 17, 18, 20, 21, 22, 26, 27, 28, 29, 32, 33, 34, 35, 36, 38, 40, 43, 46, 47, 49, 52, 53, 58, 59 as well 60. Also, a positive relation of the Coefficient of infection was observed with other slow rusting parameters (FRS, rAURPC, and *r*) with a strong R2 value that was 0.98, 0.97, and 0.95, respectively [30], [31], [49].

10. CONCLUSION

The rust pathogens of wheat are distressing as they evolve continuously, and their uredospores blow out by air over long distances. This has brought about in failure of crop resistance and severe losses to wheat production. As a promising tool for managing wheat rusts in India, fungicides belonging to the triazole group i.e., Propiconazole, Tebuconazole, Triadimefon are kept ready for efficiently controlling wheat rusts at the rate of 0.1 percent. Nevertheless, resistant cultivars have continued popular amongst the farmers as they are profitable and environmentally safer in terms of impact. Further, growers are enhanced to adopt rust-resistant cultivars. A collective strategy including consistent disease surveys, consolidation research capacity, development of novel rust-resistant varieties, and safeguarding their adoption, have led to effective management of rust diseases and enhanced wheat production in India. For the last 47 years, India had no rust epidemic even though many countries had severe outbreaks due to rust pathotypes.

11. FUTURE PROSPECTS

- ❖ The variability and continuous evolution of wheat leaf rust populations insist huge pressure on wheat breeders and researchers in general to be continuously vigilant against the emergence of novel rust races. This necessitates timeous monitoring and collaborative surveillance of variations in the virulence patterns among rust pathogens in each country and across regions.

- ❖ Durable host plant resistance to leaf rust is one of the utmost critical traits that breeding programs should invest in, permitting a lessening in the use of fungicides as well as encouraging greater stability and sustainability of yield levels.
- ❖ The use of exceedingly sophisticated and high throughput tools such as field pathogenomics, transgenics, genome editing, and next generation sequencing to study both the host and the pathogen will assist in eventually achieving broad spectrum and durable leaf rust resistance in wheat. This will subsequently result in a realization of large extents of returns on global economic investments in international wheat research.
- ❖ A multidisciplinary approach concerning pathologists, geneticists, breeders, physiologists, agronomists and bioinformaticians at different stages of research and development is necessary to develop an enhanced cultivar with stable and durable leaf rust resistance through host plant resistance approach.
- ❖ The extensive training of young researchers explicitly in the field of plant–pathogen interaction and in the usage of high throughput technologies stated above, in collaboration with universities in India, will also produce immeasurable benefits in maintaining or conserving valuable genetic materials for wheat and other economically significant crops and generate varieties that take partin specific public-good traits such as durable rust resistance.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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